Example:

H = 7.14741 g H_2O vapor/kg dry air time weighted over the FTP test cycle

$x_{NOxdexh}$ = 1.21 ppm

$$x_{NOxdexhcor} = 1.21 \cdot \frac{1}{1 - 0.0329 \cdot (7.14741 - 10.71)} = 1.08305 \text{ ppm}$$

(b) For vehicles above 14,000 pounds GVWR, apply correction factors as described in 40 CFR 1065.670.

§ 1066.620 Removed water correction.

Correct for removed water if water removal occurs upstream of a concentration measurement and downstream of a flow meter used to determine mass emissions over a test interval. Perform this correction based on the amount of water at the concentration measurement and on the amount of water at the flow meter.

§ 1066.625 Flow meter calibration calculations.

This section describes how to calibrate various flow meters based on mass flow rates. Calibrate your flow meter according to 40 CFR 1065.640 instead if you calculate emissions based on molar flow rates.

(a) *PDP calibration.* Perform the following steps to calibrate a PDP flow meter:

(1) Calculate PDP volume pumped per revolution, V_{rev}, for each restrictor position from the mean values determined in § 1066.140:

$$V_{rev} = \frac{\bar{\dot{Q}}_{ref} \cdot \bar{T}_{in} \cdot p_{std}}{\bar{f}_{nPDP} \cdot \bar{p}_{in} \cdot T_{std}}$$

Eq. 1066.625-1

Where:

$\bar{\dot{Q}}_{ref}$ = mean flow rate of the reference flow meter.

$\bar{T}_{in}$ = mean temperature at the PDP inlet.

p_{std} = standard pressure = 101.325 kPa.

$\bar{f}_{nPDP}$ = mean PDP speed.

$\bar{p}_{in}$ = mean static absolute pressure at the PDP inlet.

T_{std} = standard temperature = 293.15 K.

Example:

$\bar{\dot{Q}}_{ref}$ = 0.1651 m^3/s

$\bar{T}_{in}$ = 299.5 K

p_{std} = 101.325 kPa

$\bar{f}_{nPDP}$ = 1205.1 r/min = 20.085 r/s

$\bar{p}_{in}$ = 98.290 kPa

$$T_{std} = 293.15 \text{ K}$$

$$V_{rev} = \frac{0.1651 \cdot 299.5 \cdot 101.3}{20.085 \cdot 98.290 \cdot 293.15}$$

$$V_{rev} = 0.00866 \text{ m}^3\text{/r}$$

(2) Calculate a PDP slip correction factor, K_s for each restrictor position from the mean values determined in § 1066.140:

$$K_s = \frac{1}{\bar{f}_{nPDP}} \cdot \sqrt{\frac{\bar{p}_{out} - \bar{p}_{in}}{\bar{p}_{out}}}$$

Eq. 1066.625-2

Where:

$\bar{f}_{mPDP}$ = mean PDP speed.

$\bar{p}_{out}$ = mean static absolute pressure at the PDP outlet.

$\bar{p}_{in}$ = mean static absolute pressure at the PDP inlet.

Example:

$$\bar{f}_{nPDP} = 1205.1 \text{ r/min} = 20.085 \text{ r/s}$$

$$\bar{p}_{out} = 100.103 \text{ kPa}$$

$$\bar{p}_{in} = 98.290 \text{ kPa}$$

$$K_s = \frac{1}{20.085} \cdot \sqrt{\frac{100.103 - 98.290}{100.103}}$$

$$K_s = 0.006700 \text{ s/r}$$

(3) Perform a least-squares regression of V_{rev}, versus K_s, by calculating slope, a_1, and intercept, a_0, as described in 40 CFR 1065.602.

(4) Repeat the procedure in paragraphs (a)(1) through (3) of this section for every speed that you run your PDP.

(5) The following example illustrates a range of typical values for different PDP speeds:

TABLE 1 OF § 1066.625—EXAMPLE OF PDP CALIBRATION DATA

$\bar{f}_{nPDP}$ (revolution/s)	a_1 (m^3/s)	a_0 (m^3/revolution)
12.6	0.841	0.056
16.5	0.831	−0.013
20.9	0.809	0.028
23.4	0.788	−0.061

(6) For each speed at which you operate the PDP, use the appropriate regression equation from this paragraph (a) to calculate flow rate during emission testing as described in § 1066.630.

(b) *SSV calibration.* The equations governing SSV flow assume one-dimensional isentropic inviscid flow of an ideal gas, except that the equations can account for compressible flow. Paragraph (b)(2)(iv) of this section describes other assumptions that may apply. If good engineering judgment dictates that you account for gas compressibility, you may either use an appropriate equation of state to determine values of Z as a function of measured pressure and temperature, or you may develop your own calibration equations based on good engineering judgment. Note that the equation for the flow coefficient, C_f, is based on the ideal gas assumption that the isentropic exponent, γ, is equal to the ratio of specific heats, C_p/C_v. If good engineering judgment dictates using a real gas isentropic exponent, you may either use an appropriate equation of state to determine values of γ as a function of measured pressure and temperature, or you may develop your own calibration equations based on good engineering judgment.

(1) Calculate volume flow rate, $\overline{\dot{Q}}$, as follows

$$\dot{Q} = C_{\mathrm{d}} \cdot C_{\mathrm{f}} \cdot \frac{A_{\mathrm{t}} \cdot R \cdot p_{\mathrm{in}} \cdot T_{\mathrm{std}}}{p_{\mathrm{std}} \cdot \sqrt{Z \cdot M_{\mathrm{mix}} \cdot R \cdot T_{\mathrm{in}}}}$$

Eq. 1066.625-3

Where:

C_{d} = discharge coefficient, as determined in paragraph (b)(2)(i) of this section.

C_{f} = flow coefficient, as determined in paragraph (b)(2)(ii) of this section.

A_{t} = cross-sectional area at the venturi throat.

R = molar gas constant.

p_{in} = static absolute pressure at the venturi inlet.

T_{std} = standard temperature.

p_{std} = standard pressure.

Z = compressibility factor.

M_{mix} = molar mass of gas mixture.

T_{in} = absolute temperature at the venturi inlet.

(2) Perform the following steps to calibrate an SSV flow meter:

(i) Using the data collected in § 1066.140, calculate C_{d} for each flow rate using the following equation:

$$C_{\mathrm{d}} = \dot{Q}_{\mathrm{ref}} \cdot \frac{p_{\mathrm{std}} \cdot \sqrt{Z \cdot M_{\mathrm{mix}} \cdot R \cdot T_{\mathrm{in}}}}{C_{\mathrm{f}} \cdot A_{\mathrm{t}} \cdot R \cdot p_{\mathrm{in}} \cdot T_{\mathrm{std}}}$$

Eq. 1066.625-4

Where:

$\dot{\bar{Q}}_{\mathrm{ref}}$ = measured volume flow rate from the reference flow meter.

(ii) Use the following equation to calculate C_{f} for each flow rate:

$$C_f = \left[\frac{2 \cdot \gamma \cdot \left(r^{\frac{\gamma-1}{\gamma}} - 1\right)}{(\gamma - 1) \cdot \left(\beta^4 - r^{\frac{-2}{\gamma}}\right)}\right]^{\frac{1}{2}}$$

Where:

γ = isentropic exponent. For an ideal gas, this is the ratio of specific heats of the gas mixture, C_p/C_v.

r = pressure ratio, as determined in paragraph (b)(2)(iii) of this section.

β = ratio of venturi throat diameter to inlet diameter.

(iii) Calculate r using the following equation:

$$r = 1 - \frac{\Delta p}{p_{in}}$$

Eq. 1066.625-6

Where:

Δp = differential static pressure, calculated as venturi inlet pressure minus venturi throat pressure.

(iv) You may apply any of the following simplifying assumptions or develop other values as appropriate for your test configuration, consistent with good engineering judgment:

(A) For raw exhaust, diluted exhaust, and dilution air, you may assume that the gas mixture is incompressible and therefore behaves as an ideal gas (Z = 1).

(B) For raw exhaust, you may assume γ =1.385.

(C) For diluted exhaust and dilution air, you may assume γ = 1.399.

(D) For diluted exhaust and dilution air, you may assume M_{mix} is a function only of the amount of water in the dilution air or calibration air, as follows:

$$M_{mix} = M_{air} \cdot (1 - x_{H2O}) + M_{H_2O} \cdot x_{H2O}$$

Eq. 1066.625-7

Where:

M_{air} = 28.96559 g/mol

x_{H2O} = amount of H_2O in the dilution air or calibration air, determined as described in 40 CFR 1065.645.

M_{H2O} = 18.01528 g/mol

Example:

x_{H2O} = 0.0169 mol/mol

M_{mix} = 28.96559 · (1 − 0.0169) + 18.01528 · 0.0169

M_{mix} = 28.7805 g/mol

(E) For diluted exhaust and dilution air, you may assume a constant molar mass of the mixture, M_{mix}, for all calibration and all testing if you control the amount of water in dilution air and in calibration air, as illustrated in the following table:

TABLE 2 OF § 1066.625—EXAMPLES OF DILUTION AIR AND CALIBRATION AIR DEWPOINTS AT WHICH YOU MAY ASSUME A CONSTANT M_{mix}

If calibration T_{dew} (°C) is . . .	assume the following constant M_{mix} (g/mol) . . .	for the following ranges of T_{dew} (°C) during emission tests [a]
≤ 0	28.96559	≤ 18
0	28.89263	≤ 21
5	28.86148	≤ 22
10	28.81911	≤ 24
15	28.76224	≤ 26
20	28.68685	−8 to 28
25	28.58806	12 to 31
30	28.46005	23 to 34

[a] The specified ranges are valid for all calibration and emission testing over the atmospheric pressure range (80.000 to 103.325) kPa.

(v) The following example illustrates the use of the governing equations to calculate C_d of an SSV flow meter at one reference flow meter value:

Example:

$\dot{Q}_{ref}$ = 2.395 m³/s

$Z = 1$

M_{mix} = 28.7805 g/mol = 0.0287805 kg/mol

R = 8.314472 J/(mol · K) = 8.314472 (m² · kg)/(s² · mol · K)

T_{in} = 298.15 K

A_t = 0.01824 m²

p_{in} = 99.132 kPa = 99132 Pa = 99132 kg/(m · s²)

$\gamma = 1.399$

$\beta = 0.8$

Δp = 7.653 kPa

$$r = 1 - \frac{2.312}{99.132} = 0.922$$

$$C_\text{f} = \left[\frac{2 \cdot 1.399 \cdot \left(0.922^{\frac{1.399-1}{1.399}} - 1\right)}{(1.399-1) \cdot \left(0.8^4 - 0.922^{\frac{-2}{1.399}}\right)} \right]^{\frac{1}{2}}$$

$C_\text{f} = 0.472$

$$C_\text{d} = 2.395 \cdot \frac{101325 \cdot \sqrt{1 \cdot 0.0287805 \cdot 8.314472 \cdot 298.15}}{0.472 \cdot 0.01824 \cdot 8.314472 \cdot 99132 \cdot 293.15}$$

$C_\text{d} = 0.985$

(vi) Calculate the Reynolds number, $Re^{\#}$, for each reference flow rate, $\dot{Q}_\text{ref}$, using the throat diameter of the venturi, d_t, and the uncorrected air density, ρ. Because the dynamic viscosity, μ, is needed to compute $Re^{\#}$, you may use your own fluid viscosity model to determine μ for your calibration gas (usually air), using good engineering judgment. Alternatively, you may use the Sutherland three-coefficient viscosity model to approximate μ, as shown in the following sample calculation for $Re^{\#}$:

$$Re^{\#} = \frac{4 \cdot \rho \cdot \dot{Q}_\text{ref}}{\pi \cdot d_\text{t} \cdot \mu}$$

Eq. 1066.625-8

Where, using the Sutherland three-coefficient viscosity model:

$$\mu = \mu_0 \cdot \left(\frac{T_\text{in}}{T_0}\right)^{\frac{3}{2}} \cdot \left(\frac{T_0 + S}{T_\text{in} + S}\right)$$

Eq. 1066.625-9

Where:

μ_0 = Sutherland reference viscosity.

T_0 = Sutherland reference temperature.

S = Sutherland constant.

TABLE 3 OF § 1066.625—SUTHERLAND THREE-COEFFICIENT VISCOSITY MODEL PARAMETERS

Gas[a]	μ_0	T_0	S	Temperature range within ±2% error[b]	Pressure limit[b]
	kg/(m · s)	K	K	K	kPa
Air	$1.716 \cdot 10^{-5}$	273	111	170 to 1900	≤ 1800
CO_2	$1.370 \cdot 10^{-5}$	273	222	190 to 1700	≤ 3600
H_2O	$1.12 \cdot 10^{-5}$	350	1064	360 to 1500	≤ 10000
O_2	$1.919 \cdot 10^{-5}$	273	139	190 to 2000	≤ 2500
N_2	$1.663 \cdot 10^{-5}$	273	107	100 to 1500	≤ 1600

[a] Use tabulated parameters only for the pure gases, as listed. Do not combine parameters in calculations to calculate viscosities of gas mixtures.

[b] The model results are valid only for ambient conditions in the specified ranges.

Example:

$\mu_0 = 1.716 \cdot 10^{-5}$ kg/(m·s)

$T_0 = 273$ K

$S = 111$ K

$$\mu = 1.716 \cdot 10^{-5} \cdot \left(\frac{298.15}{273}\right)^{\frac{3}{2}} \cdot \left(\frac{273+111}{298.15+111}\right)$$

$\mu = 1.838 \cdot 10^{-5}$ kg/(m·s)

$T_{in} = 298.15$ K

$d_t = 152.4$ mm $= 0.1524$ m

$\rho = 1.1509$ kg/m^3

$$Re^{\#} = \frac{4 \cdot 1.1509 \cdot 2.395}{3.14159 \cdot 0.1524 \cdot 1.838 \cdot 10^{-5}}$$

$Re^{\#} = 1.2531 \cdot 10^6$

(vii) Calculate ρ using the following equation:

$$\rho = \frac{p_{\text{in}} \cdot MW_{\text{mix}}}{R \cdot T_{\text{in}}}$$

Eq. 1066.625-10

Example:

$$\rho = \frac{99132 \cdot 0.0287805}{8.314472 \cdot 298.15}$$

$\rho = 1.1509 \text{ kg/m}^3$

(viii) Create an equation for C_d as a function of $Re^{\#}$, using paired values of the two quantities. The equation may involve any mathematical expression, including a polynomial or a power series. The following equation is an example of a commonly used mathematical expression for relating C_d and $Re^{\#}$:

$$C_{\text{d}} = a_0 - a_1 \cdot \sqrt{\frac{10^6}{Re^{\#}}}$$

Eq. 1066.625-11

(ix) Perform a least-squares regression analysis to determine the best-fit coefficients for the equation and calculate *SEE* as described in 40 CFR 1065.602.

(x) If the equation meets the criterion of $SEE \leq 0.5\% \cdot C_{\text{dmax}}$, you may use the equation for the corresponding range of $Re^{\#}$, as described in §1066.630(b).

(xi) If the equation does not meet the specified statistical criteria, you may use good engineering judgment to omit calibration data points; however, you must use at least seven calibration data points to demonstrate that you meet the criterion. For example, this may involve narrowing the range of flow rates for a better curve fit.

(xii) Take corrective action if the equation does not meet the specified statistical criterion even after omitting calibration data points. For example, select another mathematical expression for the C_d versus $Re^{\#}$ equation, check for leaks, or repeat the calibration process. If you must repeat the calibration process, we recommend applying tighter tolerances to measurements and allowing more time for flows to stabilize.

(xiii) Once you have an equation that meets the specified statistical criterion, you may use the equation only for the corresponding range of flow rates.

(c) *CFV calibration.* Some CFV flow meters consist of a single venturi and some consist of multiple venturis where different combinations of venturis are used to meter different flow rates. For CFV flow meters that consist of multiple venturis, either calibrate each venturi independently to determine a separate calibration coefficient, K_v, for each venturi, or calibrate each combination of venturis as one venturi by determining K_v for the system.

(1) To determine K_v for a single venturi or a combination of venturis, perform the following steps:

(i) Calculate an individual K_v for each calibration set point for each restrictor position using the following equation:

$$K_v = \frac{\bar{\dot{Q}}_{\text{refstd}} \cdot \sqrt{\bar{T}_{\text{in}}}}{\bar{p}_{\text{in}}}$$

Eq. 1066.625-12

Where:

$\bar{\dot{Q}}_{\text{refstd}}$ = mean flow rate from the reference flow meter, corrected to standard reference conditions.

$\bar{T}_{\text{in}}$ = mean temperature at the venturi inlet.

$\bar{p}_{\text{in}}$ = mean static absolute pressure at the venturi inlet.

(ii) Calculate the mean and standard deviation of all the K_v values (see 40 CFR 1065.602). Verify choked flow by plotting K_v as a function of $\bar{P}_{\text{in}}$. K_v will have a relatively constant value for choked flow; as vacuum pressure increases, the venturi will become unchoked and K_v will decrease. Paragraphs (c)(1)(iii) through (viii) of this section describe how to verify your range of choked flow.

(iii) If the standard deviation of all the K_v values is less than or equal to 0.3% of the mean K_v, use the mean K_v in Eq. 1066.630–7, and use the CFV only up to the highest venturi pressure ratio, r, measured during calibration using the following equation:

$$r = 1 - \frac{\Delta p_{\text{CFV}}}{\bar{p}_{\text{in}}}$$

Eq. 1066.625-13

Where:

Δp_{CFV} = differential static pressure; venturi inlet minus venturi outlet.

(iv) If the standard deviation of all the K_v values exceeds 0.3% of the mean K_v, omit the K_v value corresponding to the data point collected at the highest r measured during calibration.

(v) If the number of remaining data points is less than seven, take corrective action by checking your calibration data or repeating the calibration process. If you repeat the calibration process, we recommend checking for leaks, applying tighter tolerances to measurements and allowing more time for flows to stabilize.

(vi) If the number of remaining K_v values is seven or greater, recalculate the mean and standard deviation of the remaining K_v values.

(vii) If the standard deviation of the remaining K_v values is less than or equal to 0.3% of the mean of the remaining K_v, use that mean K_v in Eq 1066.630–7, and use the CFV values only up to the highest r associated with the remaining K_v.

(viii) If the standard deviation of the remaining K_v still exceeds 0.3% of the mean of the remaining K_v values, repeat the steps in paragraph (c)(1)(iv) through (vii) of this section.

(2) During exhaust emission tests, monitor sonic flow in the CFV by monitoring r. Based on the calibration data selected to meet the standard deviation criterion in paragraphs (c)(1)(iv) and (vii) of this section, in which K_v is constant, select the data values associated with the calibration point with the lowest absolute venturi inlet pressure to determine the r limit. Calculate r during the exhaust emission test using Eq. 1066.625–8 to demonstrate that the value of r during all emission tests is less than or equal to the r limit derived from the CFV calibration data.

§ 1066.630 PDP, SSV, and CFV flow rate calculations.

This section describes the equations for calculating flow rates from various flow meters. After you calibrate a flow meter according to § 1066.625, use the calculations described in this section to calculate flow during an emission test. Calculate flow according to 40 CFR 1065.642 instead if you calculate emissions based on molar flow rates.

(a) *PDP*. (1) Based on the speed at which you operate the PDP for a test interval, select the corresponding slope, a_1, and intercept, a_0, as determined in § 1066.625(a), to calculate PDP flow rate, $\dot{Q}$, as follows:

$$\dot{Q} = f_{\mathrm{nPDP}} \cdot \frac{V_{\mathrm{rev}} \cdot T_{\mathrm{std}} \cdot p_{\mathrm{in}}}{T_{\mathrm{in}} \cdot p_{\mathrm{std}}}$$

Eq. 1066.630-1

Where:

f_{nPDP} = pump speed.

V_{rev} = PDP volume pumped per revolution, as determined in paragraph (a)(2) of this section.

T_{std} = standard temperature = 293.15 K.

p_{in} = static absolute pressure at the PDP inlet.

T_{in} = absolute temperature at the PDP inlet.

p_{std} = standard pressure= 101.325 kPa.

(2) Calculate V_{rev} using the following equation:

$$V_{\mathrm{rev}} = \frac{a_1}{f_{\mathrm{nPDP}}} \cdot \sqrt{\frac{p_{\mathrm{out}} - p_{\mathrm{in}}}{p_{\mathrm{out}}}} + a_0$$

Eq. 1066.630-2

p_{out} = static absolute pressure at the PDP outlet.